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AN UPPER ASYMPTOTE FOR THE THREE-PARAMETER LOGISTIC ITEM-RESPONSE MODEL

Mark A. Barton
and
Frederic M. Lord

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Abstract

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An Upper Asymptote for the Three-Parameter Logistic Item-Response Model*

Mark A. Barton

and

Frederic M. Lord

A two-parameter logistic item-response model may be expressed as

$$F(\theta) = (1 + e^{-1.7a_g(\theta-b_g)})^{-1}$$

where $F(\theta)$ is the probability of a student with ability θ passing item g. The probability of passing ranges from zero to one as θ goes from $-\infty$ to ∞.

On a multiple choice test, however, the probability of choosing the correct answer does not approach zero for low-ability students. For this reason, a lower asymptote is introduced. The resulting three-parameter model is

$$G(\theta) = c + (1 - c)F(\theta)$$

where the lower asymptote, sometimes referred to as a guessing parameter, may be set arbitrarily; or a common value may be estimated from the data; or individual values may be estimated from the data separately for each item.

An upper asymptote may likewise be introduced into the model:

$$P(\theta) = c + (\delta - c)F(\theta)$$

While $F(\theta)$ ranges from zero to one, $P(\theta)$ ranges from the lower asymptote, c, to the upper asymptote, δ.

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Even a high-ability student may make a clerical error in answering an easy item. The introduction of an upper asymptote with a value of slightly less than 1 should allow a high-ability student to miss an easy item without having his ability estimate drastically lowered.

This study of the upper-asymptote model was motivated largely by the concern that the three-parameter model might be severely penalizing high-ability students who make a clerical error on an easy item. The three-parameter model was compared to the upper-asymptote (four-parameter) model for four data sets: SAT Verbal, SAT Math, GRE Verbal, and AP Calculus AB.

The tests, all of which were developed by Educational Testing Service, are described briefly:

Scholastic Aptitude Test (SAT), Verbal: The SAT is a 75-minute, 90-item verbal test designed for applicants to undergraduate study. All items are five choice.

Scholastic Aptitude Test (SAT), Math: The mathematical part of the SAT (from a different form of the test, with different students) was analyzed as a separate data set. This 90-minute test has 85 items, 20 of which are four choice, and 65 of which are five choice.

Graduate Record Examination (GRE) Aptitude Test, Verbal: This test of verbal reasoning and reading comprehension is designed for applicants to graduate study. All of the items on this 50-minute, 80-item test are five-choice items.

College Board Advanced Placement (AP) Examination--Mathematics: Calculus AB. This is a test taken by high school students in order to receive college credit for their knowledge of elementary functions and first-semester calculus. The essay items were not included in this analysis. The objective portion lasts 90 minutes and has 45 items. All of the items are five choice.

For each of the four data sets, the following procedure was used:

1) Ability and item parameters were estimated under the three-parameter model using the program LOGIST (Wood & Lord, 1976; Wood, Wingersky, & Lord, 1976), with several thousand students. (These runs were already available.)

2) In order to reduce costs, a random subsample of 1000 students was chosen.

3) With the c_g parameters (guessing parameters) held fixed at the previously estimated values (to reduce costs), the remaining item parameters (a 's and b 's) and the abilities (θ 's) were reestimated for just the 1000 students with $\delta = 1.00$.

4) With the c_g parameters still held fixed, the a 's, b 's, and θ 's were estimated with upper asymptote values of $\delta = .99$ and $\delta = .98$, using a modified version of LOGIST on the sample of 1000 students.

The effect of the upper asymptote was measured in two ways. First, likelihoods were computed for each value of the upper asymptote ($\delta = 1.00$, $\delta = .99$, $\delta = .98$), and the asymptote value with the highest likelihood was considered the best fit. In two of the cases (GRE Verbal and AP Calculus AB) the highest likelihood was obtained with $\delta = 1.00$ (the standard three-parameter model) and in the other two cases (SAT Math and SAT Verbal) the highest likelihood was obtained with $\delta = .99$. In none of the four data sets did the highest and the lowest of the three log-likelihoods differ by more than 0.02% (more than .0002).

Second, ability estimates under the two asymptote values $\delta = 1.00$ and $\delta = .99$ were compared to see whether the change in upper-asymptote value had a large effect on the ability estimate of any individual student. Out of the 4000 students examined in the four data sets, the greatest change was an increase of .64 under the .99 upper-asymptote model. The five students most affected are summarized in Table 1. Two of these were very high-ability students, and the other three were very low-ability students. The ability estimate changed by more than the standard error of estimate in only one of the five cases. In all five cases, the .99-upper-asymptote model favored the student. The largest drop in a student's ability estimate under the .99-upper-asymptote model was .36, for a student of very low ability on the GRE Verbal. All 1000 students who took the GRE are plotted

Table 1

The Five Students with the Largest Absolute Changes

in Theta out of 4000 Examined

$\theta_{\delta=1.00}$	$\theta_{\delta=.99}$	$\theta_{\delta=.99}-\theta_{\delta=1.00}$	Standard Error of Measurement of $\theta_{\delta=1.00}$	Test
2.9	3.4	0.5	0.4	GRE Verbal
2.8	3.3	0.5	0.7	AP Calculus AB
-3.9	-3.3	0.6	1.1	SAT Verbal
-5.0	-4.4	0.6	2.7	GRE Verbal
-5.9	-5.4	0.5	4.8	GRE Verbal

Thetas have a mean of 0 and a standard deviation of 1.

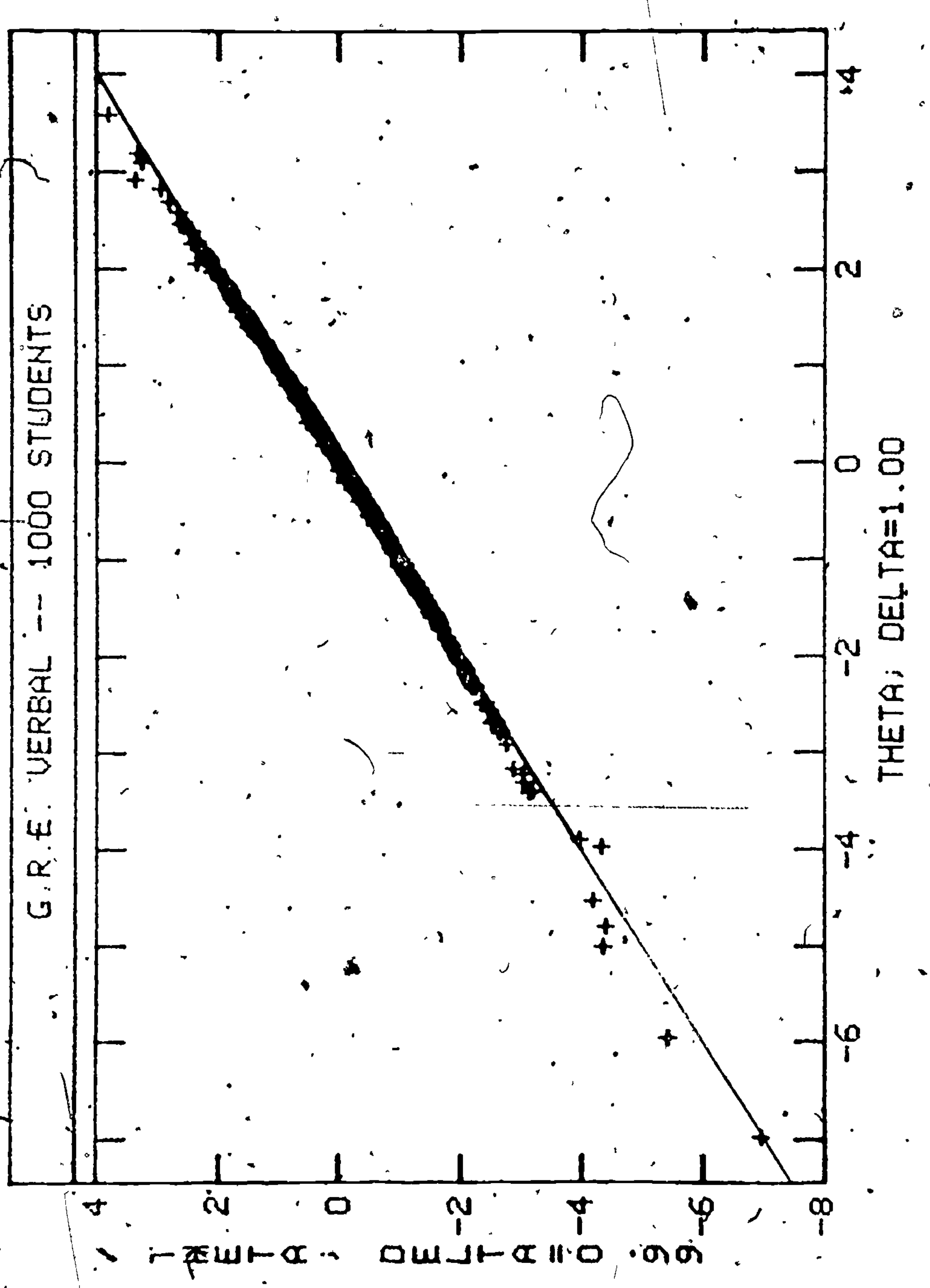
in Figure 1; in the plots for the other three data sets, points were even closer to the identity line.

One might expect more clerical errors to be made on a highly speeded test. This might result in the .99-upper-asymptote model fitting better than the 1.00-upper-asymptote model. The only highly speeded test of the four, the GRE Verbal, was fit best with the 1.00-upper-asymptote model, however, discounting this speededness hypothesis.

In view of the failure of the four-parameter model either to consistently improve the likelihood or to significantly change any ability estimates there is no compelling reason to urge the use of this model. The extra computational time required for the more complex derivatives further argues against its use.

One positive result of this study is that it suggests that the three-parameter logistic model does a better job of fitting high-ability students than some researchers (including the authors) had expected. Had we examined the normal-ogive model instead, which is less forgiving of incorrect answers to easy items by high-ability students, we would possibly have found a stronger case for the adoption of an upper asymptote of .99 or .98.

Figure 1



G.R.E. VERBAL -- 1000 STUDENTS
THETA; DELTA=1.00
THETA; DELTA=0.99
4
2
0
-2
-4
-6
-8

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Wood, R L, & Lord, F. M. A user's guide to LOGIST (ETS RM 76-4, modified). Princeton, N.J.: Educational Testing Service, 1976.

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Appendix

Formulas for derivatives of the four-parameter model*:

n = number of items.

N = number of subjects.

$D = 1.7 \ldots$

δ = upper asymptote.

u_{ij} = observed response (1 if right, 0 if wrong) for item i, subject j.

$$L_{ij} = a_i(\theta_j - b_i)$$

$$P_{ij} = c_i + (\delta - c_i)/(1 + e^{-DL_{ij}})$$

$$Q_{ij} = 1 - P_{ij}$$

The log likelihood is given by

$$\ell = \sum_{i=1}^{n} \sum_{j=1}^{N} [u_{ij} \ln P_{ij} + (1 - u_{ij}) \ln Q_{ij}] \qquad \text{(Lord, p. 58)}$$

Theta derivatives:

$$\frac{\partial \ell}{\partial \theta_j} = \sum_{i=1}^{n} (u_{ij} - P_{ij}) \frac{\left(\frac{\partial P_{ij}}{\partial \theta_j}\right)}{P_{ij} Q_{ij}}$$

and

$$\frac{\partial^2 \ell}{\partial \theta_j^2} = \sum_{i=1}^{n} \left[\frac{-\left(\frac{\partial P_{ij}}{\partial \theta_j}\right)^2}{P_{ij} Q_{ij}} + (u_{ij} - P_{ij}) \left[\frac{\left(\frac{\partial^2 P_{ij}}{\partial \theta_j^2}\right)}{P_{ij} Q_{ij}} + \frac{\left(\frac{\partial P_{ij}}{\partial \theta_j}\right)^2}{P_{ij}^2 Q_{ij}^2} (P_{ij} - Q_{ij}) \right] \right];$$

---

*The authors are grateful to Kirsten Yocom for verifying all of the derivatives.

where

$$\frac{\partial P_{ij}}{\partial \theta_j} = \frac{(\delta - c_i) D a_i}{e^{DL_{ij}} + 2 + e^{-DL_{ij}}}$$

and

$$\frac{\partial^2 P_{ij}}{\partial \theta_j^2} = \frac{-(\delta - c_i) D^2 a_i^2 (e^{DL_{ij}} - e^{-DL_{ij}})}{(e^{DL_{ij}} + 2 + e^{-DL_{ij}})^2}$$

Item-parameter derivatives:

We will drop subscripts for brevity in the following formulas.

If χ represents a_i , b_i , or c_i , and ψ represents a_i , b_i , or c_i , then

$$\frac{\partial \ell}{\partial \chi} = \sum_{j=1}^{N} (u - P) \frac{\left(\frac{\partial P}{\partial \chi}\right)}{PQ}$$

and

$$\frac{\partial^2 \ell}{\partial \chi \partial \psi} = \sum_{j=1}^{N} \left[\frac{-\left(\frac{\partial P}{\partial \psi}\right)\left(\frac{\partial P}{\partial \chi}\right)}{PQ} + (u - P)\left[\frac{\left(\frac{\partial^2 P}{\partial \chi \partial \psi}\right)}{PQ} + \left(\frac{\partial P}{\partial \chi}\right)\left(\frac{\partial P}{\partial \psi}\right) \frac{(P - Q)}{P^2 Q^2} \right]\right] ;$$

where

$$\frac{\partial P}{\partial a} = \frac{(\delta - c)D(\theta - b)}{e^{DL} + 2 + e^{-DL}} ,$$

$$\frac{\partial P}{\partial b} = \frac{-(\delta - c)Da}{e^{DL} + 2 + e^{-DL}} ,$$

$$\frac{\partial P}{\partial c} = \frac{1}{1 + e^{DL}} ,$$

$$\frac{\partial^2 P}{\partial a^2} = \frac{-(\delta - c)D^2(\theta - b)^2(e^{DL} - e^{-DL})}{(e^{DL} + 2 + e^{-DL})^2} ,$$

$$\frac{\partial^2 P}{\partial b^2} = \frac{-(\delta - c)D^2a^2(e^{DL} - e^{-DL})}{(e^{DL} + 2 + e^{-DL})^2} ,$$

$$\frac{\partial^2 P}{\partial c^2} = 0 ,$$

$$\frac{\partial^2 P}{\partial a \partial b} = \frac{(\delta - c)D^2a(\theta - b)(e^{DL} - e^{-DL})}{(e^{DL} + 2 + e^{-DL})^2} - \frac{D(\delta - c)}{(e^{DL} + 2 + e^{-DL})} ,$$

$$\frac{\partial^2 P}{\partial a \partial c} = \frac{-D(\theta - b)}{e^{DL} + 2 + e^{-DL}} ,$$

and

$$\frac{\partial^2 P}{\partial b \partial c} = \frac{Da}{e^{DL} + 2 + e^{-DL}}$$

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